FINAL REPORT

SW FireCLIME: Landscape Impacts of Fire and Climate Change in the Southwest

JFSP PROJECT ID: 15-1-03-26

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Andrea Thode - PI
Northern Arizona University

Rachel Loehman
USGS, Alaska Science Center

William Flatley
University of Arkansas

Megan Friggens
USFS Rocky Mountain Research Station

Alexander Evans
Forest Stewards Guild

Larissa Yocom
Utah State University

Don Falk
University of Arizona

Peter Fulé
Northern Arizona University

Windy Bunn
National Park Service

Craig Wilcox
Retired, USFS

Shaula Hedwall
Fish and Wildlife Service

Robert Keane
USFS Rocky Mountain Research Station

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List of Abbreviations/Acronyms

3xBAU - a three-fold annual increase of Business as Usual

6xBAU - a six-fold annual increase of Business as Usual

CCRF - Climate Change Response Framework

DFC - Desired Future Conditions

FireBGCv2 - Model that mechanistically simulates fire, vegetation, climate, and fuels dynamics (https://www.firelab.org/project/firebgcv2-landscape-fire-model). Used on the Jemez landscape in this project.

KPERP - Kaibab Plateau Ecosystem Restoration Project

LANDISII - Forest landscape model that simulates forest growth, succession and disturbance (http://www.landis-ii.org/). Used on the Kaibab landscape in this project.

NIACS - Northern Institute of Applied Climate Science

NGO - Non-governmental organization

SW FireCLIME - Southwest Fire and Climate Change project "Fire-Climate-Landscape Interactions in Montane Ecosystems"

SW CASC - USGS Southwest Climate Adaptation Science Center

VA - Vulnerability Assessment

Keywords
wildfire; climate change; management; annotated bibliography; resilience; modeling; co-production; vulnerability analysis; climate adaptation; Southwest; New Mexico; Arizona;

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We would like to thank the Northern Institute of Applied Climate Science (NIACS) for their willingness to let us use their framework and for their encouragement, thoughts, and edits in creating our Fire-Climate Adaptation Menu. Additionally, our Kaibab Fire and Climate Adaptation Workshop would not have happened or been as successful without our NIACS partners. In particular we would like to highlight the important contributions of Courtney Peterson, Chris Swanston, Maria Janowiak, and Leslie Brandt. We thank Courtney Peterson for summarizing the workshop and allowing us to use that text in this report.

The Kaibab National Forest was critical in the development of our Kaibab Fire and Climate Adaptation Workshop. In particular, we want to thank Alex Spannuth, Ariel Leonard, and Andrew Leiendecker, as well as Valerie Stein Foster. These folks worked as part of the planning team to make the workshop applicable and meaningful on the ground.

Over the time span of this project we had two different coordinators. The first was Corinne Dolan who is amazing, organized and hilarious; which are three traits needed when herding this many cats. The second was Martha Sample, who helped to push this project through to the end when everyone else was on their last legs. She has been an amazing asset to the team.

Abstract

The Southwest Fire-Climate-Landscape Interactions in Montane Ecosystems project (SW FireCLIME) aimed to evaluate how fire regimes, fuels, and fire effects may shift across Southwest landscapes as climate changes and assess the implications of changing regimes for management programs. It included a four-phase process that brought together regional scientists and managers to understand the implications of current science and to identify potential measures that can be implemented by the management community. The four phases included 1) science synthesis, 2) modeling interactions of climate, fire, and ecosystems with different management applications, 3) development and testing of a climate-fire vulnerability assessment, and 4) development and testing of a fire-climate adaptation menu. The project outputs include five webinars, five presentations, a special session at a conference, two workshops, multiple science-manager engagement sessions, three peer-reviewed journal articles, two General Technical Reports, an online searchable annotated bibliography, project website with links to all deliverables, a “Science you can use newsletter”, and a JFSP success story video that highlights SW FireCLIME. Outcomes also include the development of new science, new tools, and management strategies directly focused on helping managers adapt to fire regimes and ecosystems altered by climate change.

Objectives

The specific objectives of this project were to:

1. Synthesize current scientific understanding of changes in climate, fire regimes and fuels, and the implications of those changes for land management,
2. Collaboratively develop and model climate-management scenarios that can be used in a time of uncertainty to guide development and implementation of management strategies,
3. Jointly interpret the climate-management modeling results to develop management case studies that address changes in climate, fire regimes, and fuels,
4. Develop a framework for assessing the vulnerability of landscape components to changes in fuels and fire regimes that can be used to identify at-risk resources and guide management actions.

We designed a four-phase process that brought together regional scientists and managers to understand the implications of current science and to identify potential measures that can be implemented by the management community. These four phases overlapped, built upon each other, and sometimes ran in parallel:

Phase 1: Science synthesis - extensive review and synthesis of literature on changing climate and fire regimes and ecosystem impacts across the southwestern U.S., and a regional workshop evaluating the knowledge base and knowledge gaps. This phase of the project produced a large annotated bibliography organized around important linkages among climate, fire, and ecosystem effects, as well as a peer-reviewed journal article in preparation.

Phase 2: Modeling interactions of climate, fire, and ecosystems for management applications - assessment of management potential to mitigate unwanted impacts of climate changes and shifting fire regimes on ecosystems, using two complex ecosystem process models in two southwestern forested ecosystems. This phase of the project produced several webinars, conference presentations, and a peer-reviewed journal article.

Phase 3: Vulnerability assessment - development and application of a novel, flexible, and management-oriented tool for assessing ecosystem vulnerability to climate-fire interactions. This phase produced the VA tool, several webinars, conference presentations, a General Technical Report, and two case studies.

Phase 4: Climate adaptation toolbox - development of a menu of adaptation strategies and approaches for managing fire under future climate conditions. This menu was tested at a Climate Adaptation Workshop that we co-developed with the Kaibab National Forest and the Northern Institute of Applied Climate Science (NIACS) group.

This phase produced a webinar, workshop, conference presentation, list of fire-climate specific adaptation strategies, and a peer-reviewed journal article in preparation.

Our original ideas and plans evolved throughout the project and we met all these objectives such that the effect of SW FireCLIME will extend well past the bounds of the originally proposed project.

One unexpected outcome of this project is a case study in co-production of science. SW FireCLIME originally had 15 co-principle investigators, one collaborator, and one analyst. Of the co-PIs and collaborators, five people were from academia, three from non-governmental organizations, three from agency research programs, and five were from federal land management agencies. This project not only met the objectives stated above but is also a successful example of the co-production of science. All co-PIs were involved in the project from the writing of the proposal throughout the submission of this final report. Additional land managers were brought in during the first workshop, modeling, vulnerability assessment, and final workshop, to consult, test, and improve the different parts of the project. Managers provided invaluable perspectives and feedback, ensuring that our deliverables are meaningful and useful for local decision-making processes. This project also demonstrated that successful co-production takes more time, planning, and communication, than research conducted without such collaboration.

Additionally, work from this project has helped to create a new partnership between the USGS Southwest Climate Adaptation Science Center (SW CASC), members of this project, and the Southwest Fire Science Consortium (SWFSC). This partnership is working to fund a coordinator for a proposed SW Climate Adaptation Network to bring disparate efforts together with an overarching plan on how to best work to implement climate adaptation in the Southwest. This coordinator will work with the SWFSC coordinator and others to continue to develop and formalize this network across agencies, academia, and non-governmental organizations (NGOs).

Background

The need to understand the impact of climate change on ecosystems is more urgent than ever. Managers need current, defensible information on how landscapes will respond to the synergistic interactions of climate and disturbance processes. They must have this information to guide management strategies that maintain ecosystem resilience and avoid large-scale tipping points (Walker et al. 2002). Research is ongoing, but predictions of post-fire landscape change and climate-driven stressors remain highly uncertain. Land managers must be able to move forward in the face of that uncertainty.

Many modeling and empirical studies predict shifts in fuels characteristics and plant communities in response to changing climate at decadal and longer time scales (e.g., Lawler et al. 2006; Gonzalez et al. 2010; Rehfeldt et al. 2012). Superimposed on these shifts are severe large-scale disturbances (e.g., wildfires) that can reorganize ecosystems on much shorter time scales of weeks to months (Overpeck et al. 1990; Adams 2013). Tipping points are critical thresholds at which even small perturbations radically and persistently reorganize system patterns or processes (Falk et al. 2019).

In the Southwest (Arizona and New Mexico), reorganization may represent a tipping point in which changing climate and disturbance processes create novel fuelscapes, thus setting the stage for future fire regimes that are very different from those that have existed in the recent past (Van de Water and Safford 2011). We know that fire seasons are longer and are associated with drier conditions and warmer temperatures (Westerling 2016; Kitzberger et al. 2017). In the Southwest, total area burned and area burned at high severity has increased over the last several decades and that increase is strongly related to changes in vapor pressure deficit (VPD) and temperature (Singleton et al. 2019, Mueller et al. 2020). Changes in fire regimes will likely alter fire behavior and occurrence as vegetation composition and configuration changes (Lenihan et al. 2003; Loehman et al. 2011). Evidence from western forested ecosystems suggests that interactions between climate and fire will have lasting effects that alter the ecosystem services and values historically provisioned by these landscapes. This is especially true in the Southwest, where the adaptive capacity of ecotone regions has already been overwhelmed in multiple instances (e.g. Falk et al. 2013; Haffey et al. 2018). These changes pose serious threats to ecosystem integrity and resilience, and profound challenges to ecosystem managers. Understanding how to manage for changing future fire regimes and fuel conditions will be the central challenge for scientists and managers for decades to come.

Resource managers are faced with the challenge of identifying and implementing adaptation strategies that can address the threats posed by changes in climate and fire regimes —despite uncertainties— while still working towards larger goals and objectives. Resource managers engage in the development of adaptation strategies under the guidance of agency mandates that outline requirements and accounting processes for land management plans. For instance, the 2012 Planning Rule Framework developed by the Forest Service created a responsive planning process that allows for adaptation to changing conditions, including climate change, to improve management based on new information and monitoring. As key players between research and practice, managers need not only reliable and current information on the relationships between climate change, fire regimes, and ecosystem effects, but also tools to transform knowledge into action (Millar et al. 2007).

Various adaptation strategies may be considered appropriate depending on management goals, timelines, and available resources. These will likely range from actions that slow or stall anticipated effects (resistance), those that improve the capacity of the ecosystem to recover or adapt to changes (resilience), and those that actively facilitate and guide change (transition) (Millar et al. 2007; Swanston et al. 2016). Such regional and local differences necessitate a flexible, responsive framework that enables managers to formulate a response plan suited to their individual circumstances (Swanston et al. 2016).

The Climate Change Response Framework (CCRF) and stepwise ‘Adaptation Workbook’ process developed by Swanston, Janowiak, and others (Swanston & Janowiak 2012; Janowiak et al. 2014; Swanston et al. 2016) provides a process for managers to move forward in the face of climate change and the uncertainty of the different effects on ecosystems. The CCRF empowers managers to systematically consider their goals and objectives through the lens of climate change threats and opportunities, and to identify adaptation actions appropriate to their particular situation. Importantly, the structured process documents intentionality in considering how to achieve goals in light of climate challenges (Fig. 1). The products from the first three phases of SW FireCLIME feed directly into the “ASSESS” step (Fig. 1). To assist with the exploration and selection of adaptation actions, this process uses a ‘menu’ (list) of adaptation strategies with nested approaches and example tactics. Adaptation menus provide non-prescriptive, dynamic options to managers facing complex climate challenges (Swanston et al. 2016). In the final, fourth phase of SW FireCLIME we created a *Climate-Fire Menu of Adaptation Strategies and Approaches* and tested that menu through a climate adaptation workshop with the Kaibab National Forest.

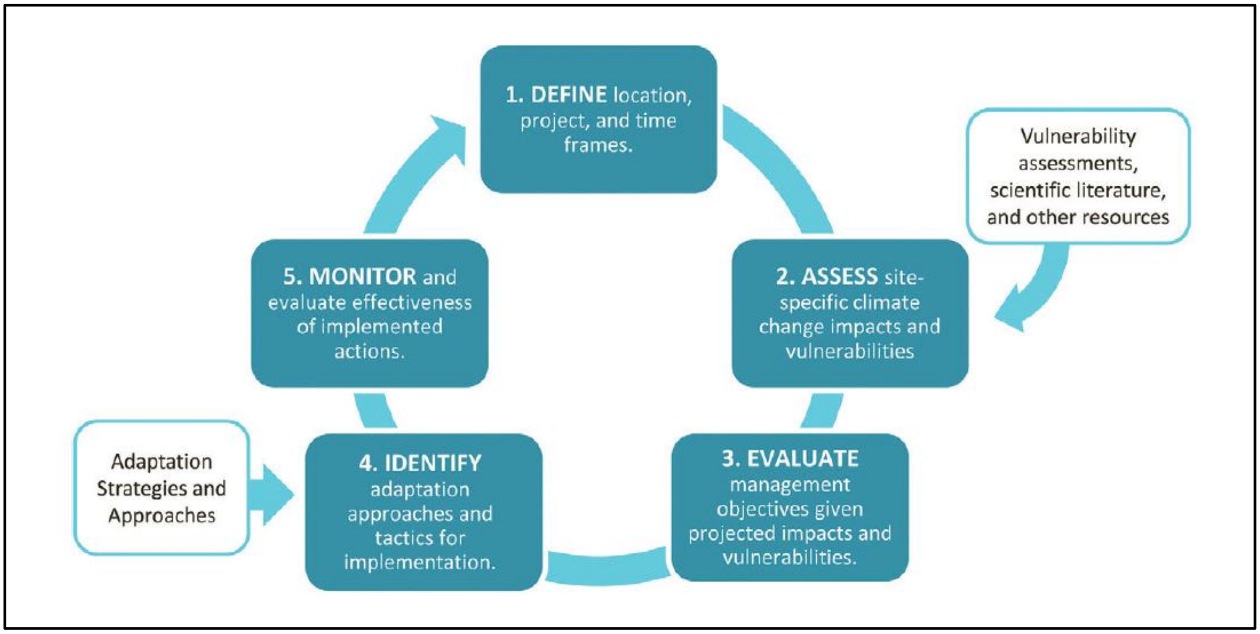

Figure 1: The Climate Change Response Framework ‘Adaptation Workbook’ process. Southwest FireCLIME phases 1-3 feed directly into step 2. The SW FireCLIME menu of adaptation strategies and approaches are an input in step 4 (from Swanston et al. 2016).

In order to provide managers with current, defensible information on how landscapes will respond to the synergistic interactions of climate and disturbance processes, we synthesized recently published literature and reports describing wildfire research on ecosystems in the southwest. We address some of the knowledge gaps identified by applying state of the art fire simulation modeling to two southwestern landscapes. Additionally, we developed a vulnerability assessment (VA) tool designed specifically to facilitate decision making by land managers even where future fire-climate and ecosystems responses are characterized by uncertainty. Finally, we adopted the CCRF framework to translate synthesis, modeling, and VA case studies into information that resource managers can use to guide management strategies that will maintain ecosystem resilience and avoid large-scale tipping points.

Phase 1: Science Synthesis

To start this project, we synthesized the current literature related to climate change and fire. The focus was on the Southwest, although other material that was considered pertinent to the Southwest was included. This phase included collecting relevant literature; developing a conceptual diagram of important relationships between climate change, fire regimes and ecosystem effects; finding literature pertinent to each of the important relationships in the conceptual diagram, conducting a workshop to ensure we captured field experience and expert knowledge, and the development of an annotated bibliography that is online and searchable as well as in a printed format.

Materials and Methods

We began the project by synthesizing current scientific understanding of climate effects on fire regimes, fuels, and ecosystems. The team identified and assessed over 250 published papers relating to climate change and fire in the Southwest. The literature search was initiated with a request to the broad group of SW FireCLIME collaborators requesting any sources that cover the broad topics of fire, climate, and vegetation in the Southwest. We included peer-reviewed articles (empirical studies, modeling studies, climate change modeling, meta-analysis, literature reviews, and editorials/opinions) and non-peer reviewed sources (general technical reports, abstracts, project reports, incident reports, dissertations/theses, interviews). Our focus was on information applicable to the Southwest, but we included studies that examined vegetation or fire-climate dynamics across the broader western US. We further supplemented the papers submitted by the team with targeted, topical searches of the literature using the Web of Science, Google Scholar, and references within the previously identified papers.

The SW FireCLIME team also developed a conceptual diagram of climate, fire regime and ecosystem effects components and their linkages to each other. (Fig. 2). The chosen components for each of the three categories (Climate, Fire Regime and Ecosystem Effects) capture the most important aspects of that category while simplifying and reducing the overall number of components. There are 48 unique "linkages" identified here (Fig. 2). We acknowledge that there are feedback cycles and that this is a much more complicated network, but this conceptual diagram has proven a valuable way to organize what is known about climate/fire interactions with ecosystems.

Once papers were collected, we used NVivo Pro v. 11 to digitally tag specific words and phrases within the papers according to different topics, or 'nodes.' First papers were classified according to a set of broad descriptors, e.g. source, geographic scope, vegetation type, time period. Next, individuals read through the papers digitally tagging portions of text within PDFs with specific topic nodes. These topic nodes directly related to the conceptual diagram described above (Fig. 2). This enabled us to search or extract paragraphs of text that applied to any of the listed topics. For example, once the NVivo database of coded papers was developed, a user could identify all text across the entire set of papers that were coded with the topics "eco – tree regeneration" and "fire – severity". Once all the coding was done, informal summaries of each of the 48 linkages were created in preparation for the science synthesis workshop.

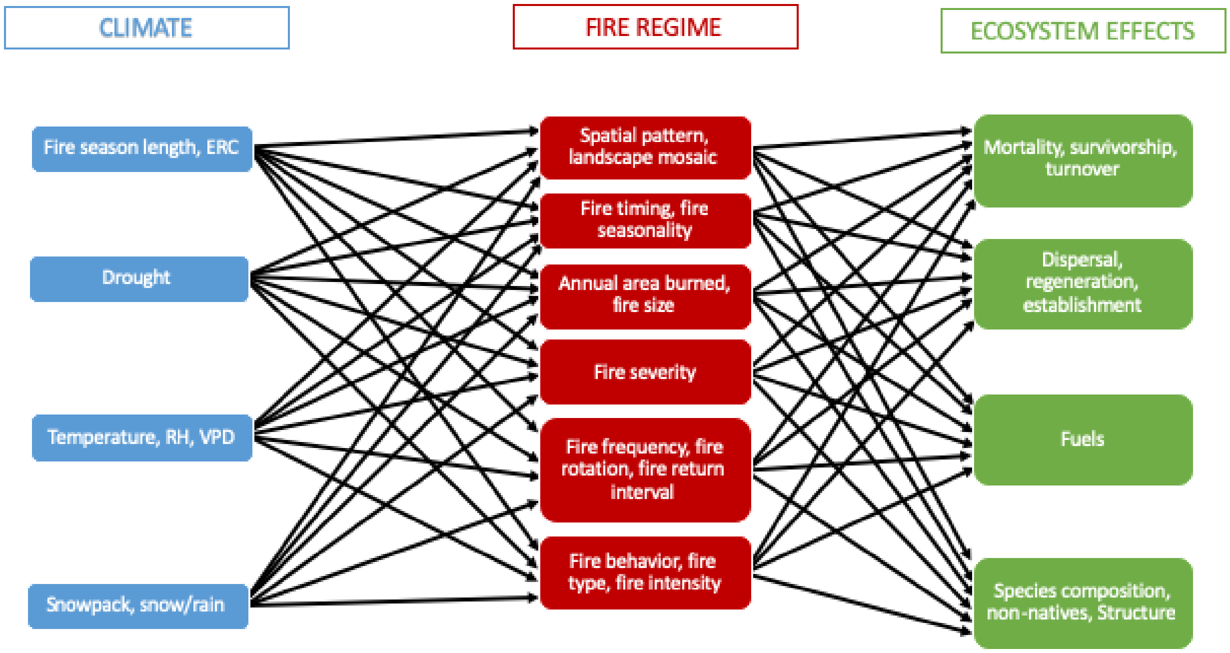

Figure 2. Conceptual diagram of climate, fire regime and ecosystem effects components and their linkages to each other. The chosen components for each of the three categories (Climate, Fire Regime and Ecosystem Effects) capture the most important aspects of that category while simplifying and reducing the overall number of components. There are 48 unique "linkages" identified here.

We presented and discussed the initial results of the fire-climate literature search in a facilitated **Science Synthesis Workshop.** This workshop was convened in Albuquerque, NM in September 2016 and was attended by 47 people representing land managers, scientists active in fire-climate research, and NGOs. This workshop was invaluable for guiding subsequent work in the project toward information and outcomes that could be most directly applied in land management

Results and Discussion

Due to quickly changing information in the field of climate and fire, we decided to develop a dynamic, interactive annotated bibliography from the literature review and input from the workshop. The summaries used in the workshop were useful, but always changing. Therefore, we created summaries by publication, allowing new information to be easily added. Each of the 190 records in the annotated bibliography includes a citation for the publication, study location, ecosystems types included in study, a summary focused on what the authors did and why, summary of the study's findings, and then publication findings for each specific linkage extracted from the overall summary. The summary of findings focuses on the climate components effects on fire regime components or fire regime component effects on ecosystem components.

This information is being produced in a general technical report, but is also presently available as a searchable website (www.frames.gov/swfireclime/bibliography) hosted by the Fire Research and Management Exchange System (FRAMES). The website allows a user to search using standard parameters such as author, ecosystem, keywords, title, and description. However, the real value and power of the website allows users to search by any of the 48 linkages between climate, fire regimes, and ecosystem effects and returns all papers that address that linkage. The record for any single paper can be viewed to find a summary and descriptions of all the linkages that paper addresses. These functionalities are not available anywhere else.

An additional deliverable from this phase of the project is a peer-reviewed journal manuscript on landscape-scale factors that regulate the fire-climate relationship. Elevation in the Southwest ranges from approximately 0 to 4000 meters. Precipitation ranges from <10 to >100 cm per year across the region, and average annual temperatures range from <5 to >20°°C. Across these wide biophysical gradients, fuel productivity and flammability vary widely and systematically. We analyzed gradients of climate, fuel productivity, and fire regime properties (such as mean fire return interval) across broad vegetation classes (scrub, desert grass, grass, shrub, woodland, dry forest, and mixed conifer). These vegetation groups vary systematically with elevation, net primary productivity (NPP), precipitation, temperature, and vapor pressure deficit (VPD) (Fig. 3).

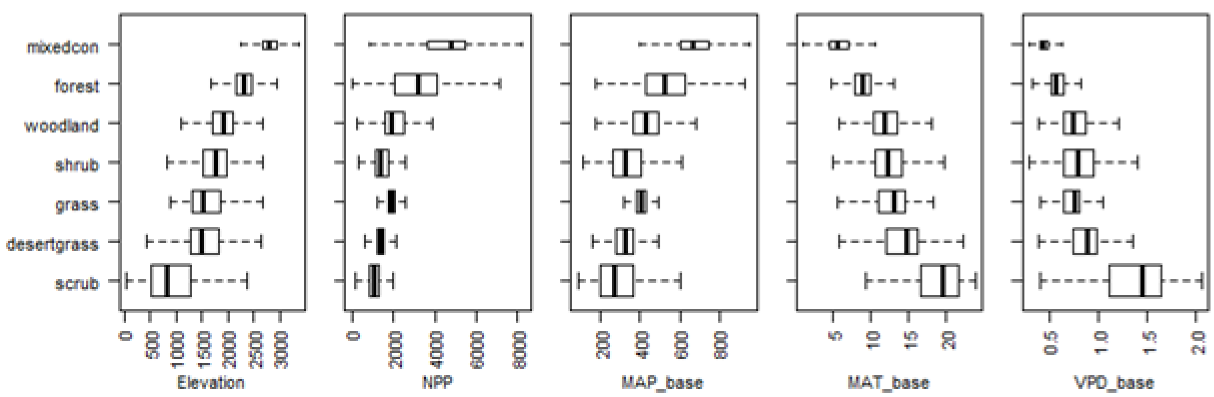

Figure 3. Broad vegetation classes (shrub, desert grass, grass, woodland, dry forest, and mixed conifer) versus elevation, net primary productivity (NPP), precipitation, temperature, and vapor pressure deficit (VPD).

We found strongly systematic patterns of variation in multiple factors that are important in fire regimes, such as biomass production (NPP). Collectively, these patterns of variation lead us to postulate a mechanism for the observed peak in fire frequency at middle elevations (Fig. 3).Fire frequency is a more complex response variable, as it integrates landscape position and topography; fuel mass, structure, and condition; and weather variables such as prevailing winds during fire season. Nonetheless, the overall fire regime conformed to our prediction of a modal peak in fire frequency at mid-elevations (Fig. 4). The full manuscript with more detail on this analysis is in the submission process and will be available in 2021.

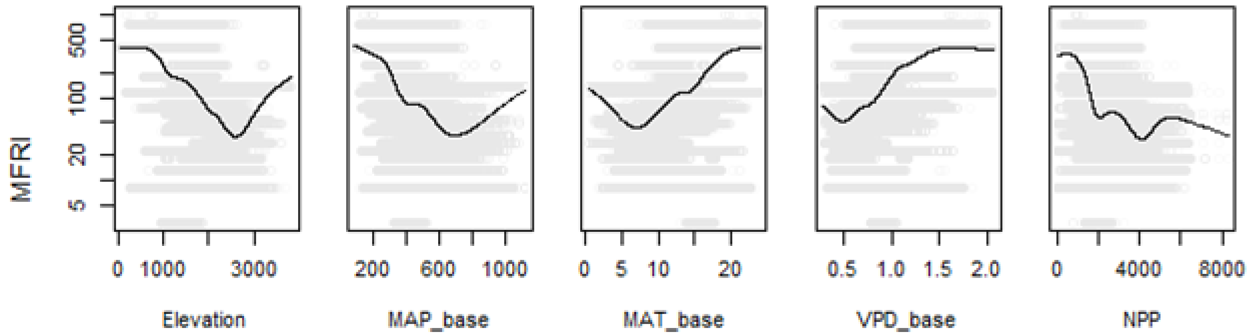

Figure 4. Mean fire return interval versus elevation, net primary productivity (NPP), precipitation, temperature, and vapor pressure deficit (VPD).

Phase 2: Modeling interactions of climate, fire, and ecosystems

Climate changes and associated shifts in ecosystems and fire regimes present enormous challenges for the management of landscapes in the Southwest. A central question is whether management strategies can maintain or promote desired ecological conditions under projected future climates. We modeled wildfire and forest responses to climate changes and management activities using two ecosystem process models: FireBGCv2, simulated for the Jemez Mountains, New Mexico, and LANDIS-II, simulated for the Kaibab Plateau, Arizona. This phase of our project resulted in a publication: *Can Land Management Buffer Impacts of Climate Changes and Altered Fire Regimes on Ecosystems of the Southwestern United States?* (Loehman et al. 2018).

Methods

Two complex, ecosystem process models, each parameterized and calibrated for a different southwestern landscape, were used to assess climate-fire-ecosystem interactions and management effectiveness (Fig. 5). Models and landscapes were: the FireBGCv2 ecosystem process model (Keane et al. 2011), modeling a 180,000 ha landscape in the Jemez Mountains of north central New Mexico (FireBGCv2-Jemez), and the LANDIS-II forest landscape model (Scheller et al. 2007), modeling a 335,000 ha landscape on the Kaibab Plateau of northern Arizona (LANDIS-Kaibab). Both landscapes are predominantly forested, with moisture and elevation gradients that dictate a pattern of drier, low elevation piñon-juniper forests or woodlands, middle-elevation ponderosa pine or dry mixed conifer dominated forests, and upper elevation mesic mixed conifer or spruce-fir forests. Each modeling experiment consisted of replicated 100-year simulations for factorial scenarios of climate (three levels) and management (four levels). Climate factors were a contemporary scenario and two future climates—"Warm-Dry" (CCSM4 RCP 4.5) and "Hot-Arid" (HadGEM2ES RCP 8.5). Management factors, derived from available prescriptions and burn plans for the study areas, then refined with input from southwestern fire and land managers, were a fire suppression scenario, a current treatment scenario, and two intensified treatment scenarios (Table 1). A suite of fire regime and ecosystem variables were used to evaluate model outcomes (Table 2), produced at annual time steps in

FireBGCv2 or every five years for LANDIS-II. Fire regime and ecosystem metrics were summarized across scenario replicates for each time step.

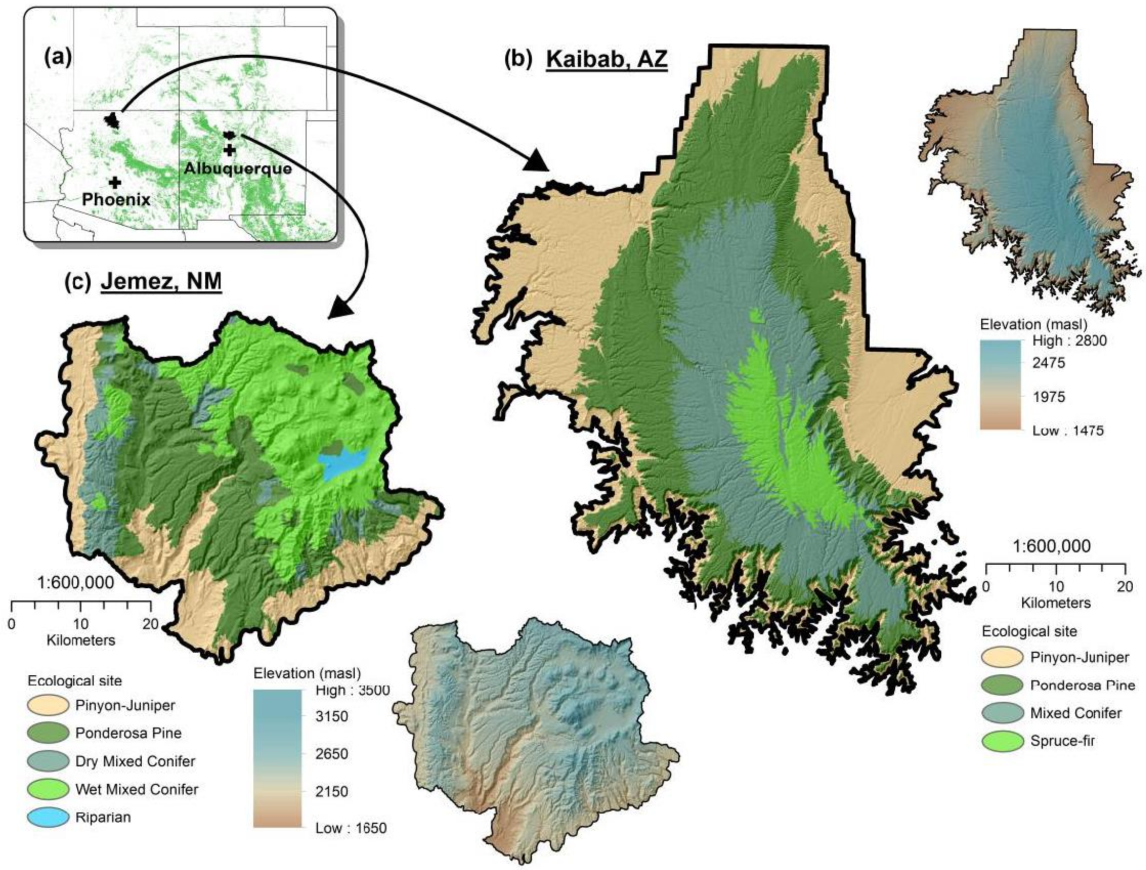

Figure 5. (**a**) Jemez, NM (FireBGCv2-Jemez) and Kaibab, AZ (LANDIS-II-Kaibab) study areas. Green shading denotes distribution of forests that historically experienced high frequency (≤35 Year Fire Return Interval) low- to mixed-severity fires (Fire Regime Group 1, LANDFIRE Program, Rollins 2009); (**b**) FireBGCv2-Jemez ecological setting and surface elevation; (**c**) LANDIS-II-Kaibab ecological setting and surface elevation (from Loehman et al. 2018, Figure 1).

Table 1. Treatment parameters for the business-as-usual (BAU) and two intensified management factors (3xBAU, 6xBAU). Forward slashes (/) separate parameter values for BAU, 3xBAU, and 6xBAU scenarios where applicable. Values without forward slashes are held constant across model scenarios.

Treatment parameters	**FireBGCv2-Jemez**	**LANDIS-II-Kaibab**
Thinning plus prescribed fire		
Annual area treated (ha)	**BAU / 3xBAU / 6xBAU**	**BAU / 3xBAU / 6xBAU**
Ponderosa pine site	461 / 1,382 / 2,765	858 / 2,575 / 5,150
Dry mixed conifer site	120 / 361 / 722	307 / 922 / 1,844
Maximum size of individual treatments (ha)	4,097	3,231
Stand basal area minimum threshold to treat (m^2/ha)		
Ponderosa pine site	4.6	Not Applicable
Dry mixed conifer site	6.9	Not Applicable
Individual tree minimum, maximum DBH (cm; FireBGCv2) or minimum, maximum age (LANDIS-II)	1, 40	1, 100
Retention species		
Ponderosa pine site	Ponderosa pine	Ponderosa pine
Dry mixed conifer site	Ponderosa pine, limber pine, white fir, Douglas-fir, aspen	Ponderosa pine, limber pine, white fir, Douglas-fir
Fraction of slash left on site after thinning (%)	10	Not Applicable
Prescribed fire only		
Maximum prescribed fire intensity (kW m^{-1})	30	Not Applicable

Ponderosa pine site	461 / 1,382 / 2,765	858 / 2,575 / 5,150
Dry mixed conifer site	120 / 361 / 722	307 / 922 / 1,844
Maximum size of individual treatments (ha)	4,097	3,231
Minimum, maximum stand age for treatment (yrs)	100, 500	Not Applicable
Rx Fire intensity minimum, maximum (kW/m)	2, 30	Not Applicable

Table 2. Fire regime and ecosystem variables for each model and landscape. Note that the metrics are similar but models calculate forest biomass, forest structure, and high-severity wildfire area burned differently (From Loehman et al. 2018, Table 1).

	FireBGCv2-Jemez	LANDIS-II-Kaibab
FIRE REGIME METRICS		
Point fire return interval	No. of simulation years/total number of wildfires per pixel	No. of simulation years/total number of wildfires per pixel
Area burned	Area of all wildfires (ha)	Area of all wildfires (ha)
High severity area burned	Area of all wildfires with tree mortality >70% (ha)	Area of all fires with >50% crown fraction burned (ha)
ECOSYSTEM METRICS		
Vegetation composition	Proportional species biomass (%)	Proportional species biomass (%)
Forest structure	Proportional species structural stage [a] (%)	Proportional species age class [b] (%)
Forest production	Basal area by species (m^2/ha^{-1})	Biomass by species, g/m^{-2}

a FireBGCv2-Jemez structural stages correspond to the following diameter classes (cm): 2 ≤ saplings ≤ 10, 10 < pole ≤ 23, 23 < mature ≤ 50, 50 < large ≤ 100, very large > 100; b LANDIS-II-Kaibab age classes correspond to the following: young 0 to 49 years, mid 50 to 99 years, and old > 100 years.

Results and Discussion

We used FireBGCv2 and LANDIS-II modeling experiments to address three primary questions: 1) How might future climates cause fundamental changes in fire regimes? 2) How might future climates change forest composition, structure, and productivity? 3) Can modeled management strategies maintain historical forest composition, structure, and productivity?

How will climate changes alter southwestern fire regimes?

The two models varied in their assessments of climate change impacts on fire frequency, area burned, and high severity area burned. Differences in model outcomes are related to varying model mechanics (see Loehman et al. 2018 for details). For FireBGCv2-Jemez, future climate increased **wildfire frequency** relative to contemporary climate, for all management scenarios. In contrast LANDIS-II-Kaibab fire return intervals showed little change in response to climate, but management activities reduced fire frequency, area burned, and high severity area burned. Climate changes resulted in increased **annual area burned** with Warm-Dry and Hot-Arid climates in FireBGCv2-Jemez relative to contemporary climate (Fig. 4a), consistent with other work showing climate-driven increases in area burned in the western US, and in particularly those in which a small fraction of fires (“megafires”) become very large despite fire suppression efforts (Westerling et al. 2006, Littell et al. 2009, Running 2006, Adams 2013). For FireBGCv2-Jemez, **area burned in high severity fire** (fires that resulted in >70% tree mortality in stands) was small (less than one percent of the total area of managed forest), but in some replicate-years, as much as 1700 ha (about two percent, Contemporary climate) or 5000 ha (about seven percent, Hot-Arid climate) of dry forested area burned annually at high severity. There was no clear impact of management on median high-severity annual area burned; however, increasing treatment intensity reduced the upper range of high-severity burned area under Hot-Arid climate (Fig. 6). Treatments had no effect on the extreme high-severity fire (outlier) years in the Hot-Arid climate scenarios. For LANDIS-II-Kaibab, annual burned area and high severity area burned were insensitive to climate, but management treatments (with the exception of suppression only scenarios) reduced both the total burned area and the area of high-severity fire (Fig. 7).

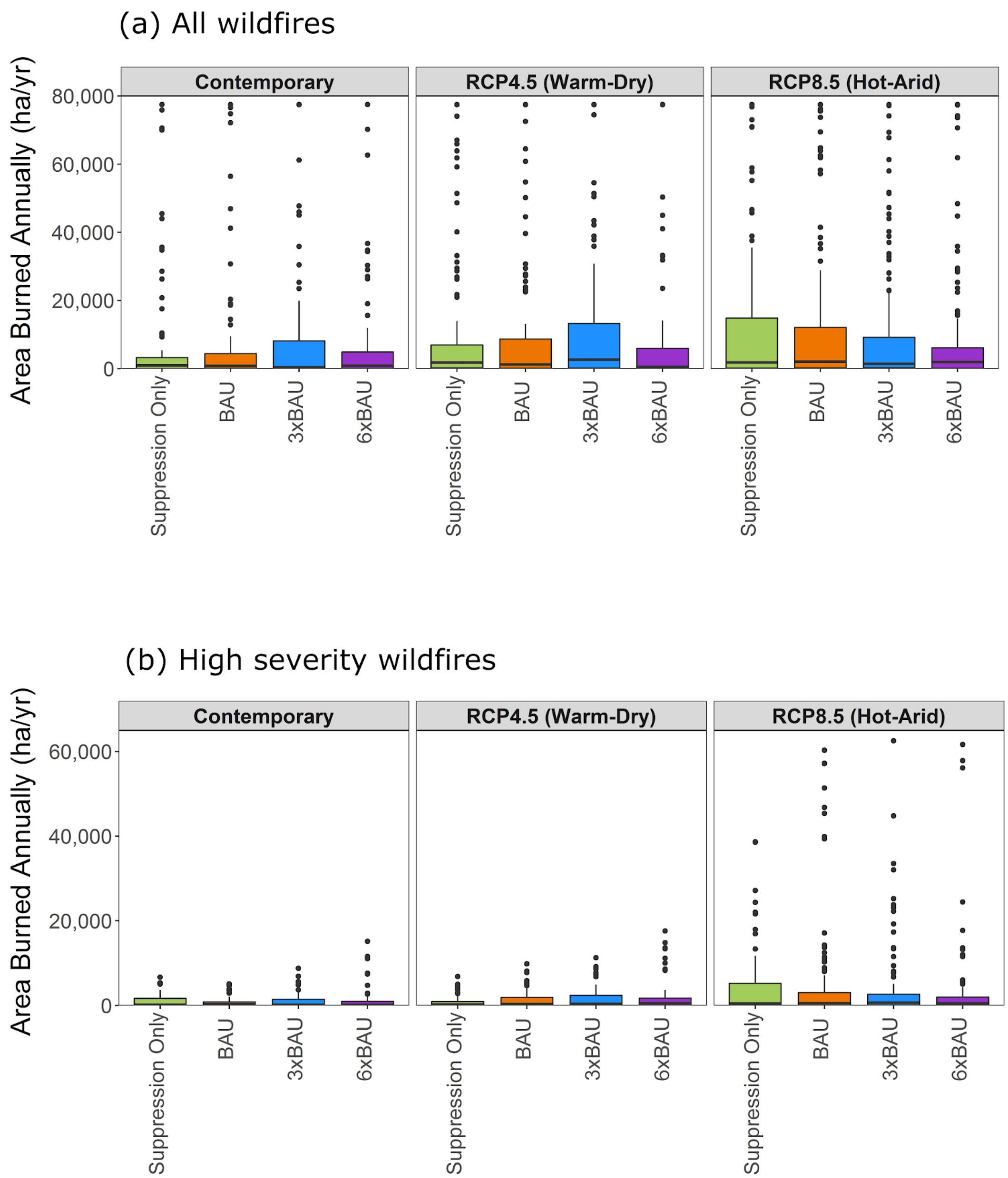

Figure 6. FireBGCv2-Jemez wildfire area burned annually (ha) in ponderosa pine and dry mixed conifer sites in (a) wildfires of all types and (b) high-severity wildfires (tree mortality >70%) for factorial combinations of management (Suppression Only; BAU, 76-year treatment rotation; 3xBAU, 22-year treatment rotation; 6xBAU, 11-year treatment rotation) and climate (contemporary; Warm-Dry; Hot-Arid). Boxplots show median, 25th, and 75th percentile wildfire area burned and outliers calculated for the pool of all replicates and all years for each scenario. The combined area of ponderosa pine and dry mixed conifer sites is 77,489 ha. (from Loehman et al. 2018, Figure 7).

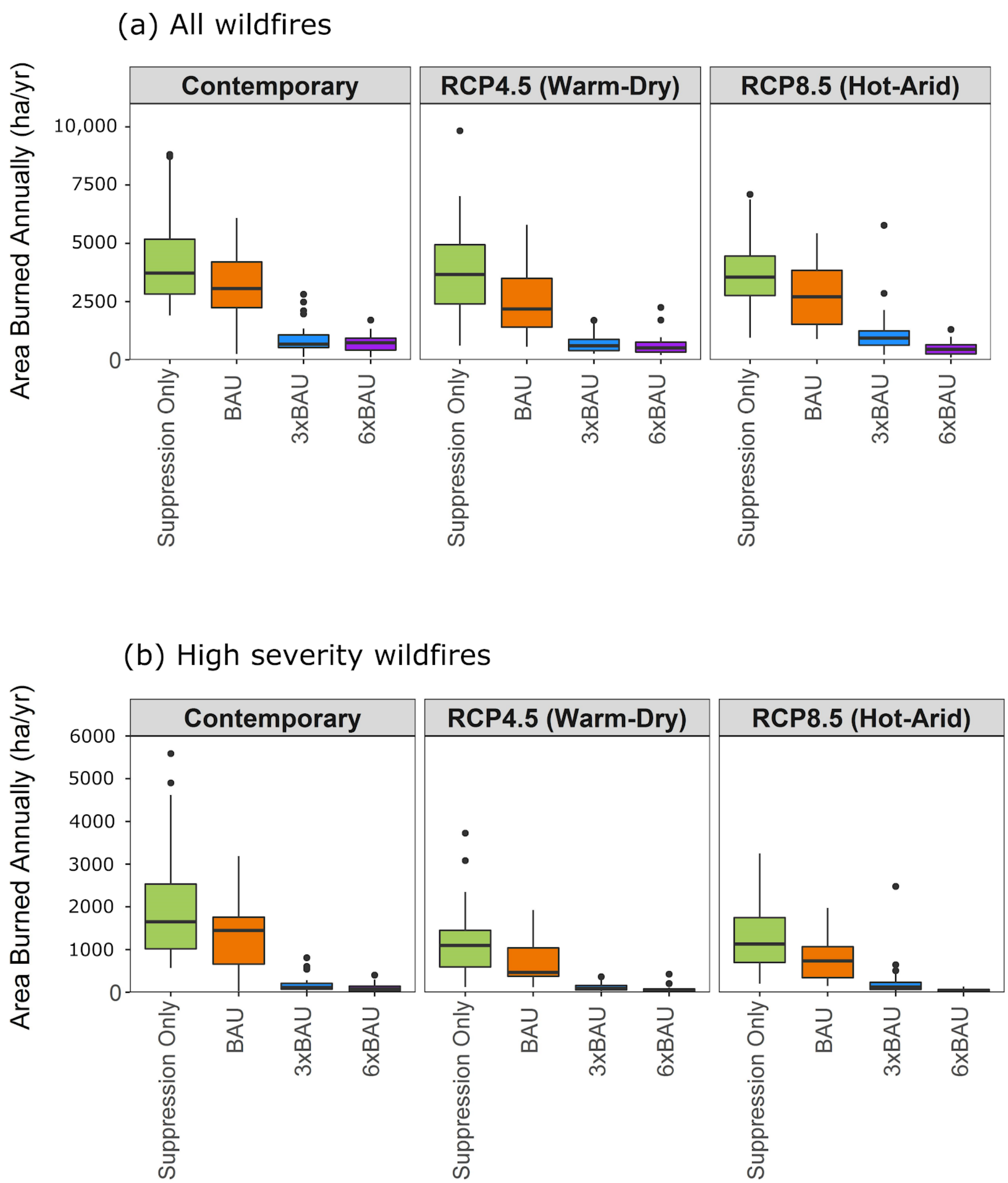

Figure 7. LANDIS-II-Kaibab wildfire area burned annually (ha) in ponderosa pine and dry mixed conifer sites for (a) wildfires of all types and (b) high-severity wildfires (>50% of crown burned) for factorial combinations of management (Suppression Only; BAU, 76-year treatment rotation; 3xBAU, 22-year treatment rotation; 6xBAU, 11-year treatment rotation) and climate (Contemporary; Warm-Dry; Hot-Arid). Boxplots show median area burned,
25th and 75th percentiles, and outliers among replicates and fire years for each scenario. The combined area of ponderosa pine and dry mixed conifer sites is 155,439 ha. (from Loehman et al. 2018, Figure 8).

How will climate changes alter southwestern forest composition, structure, and productivity?

Simulated Hot-Arid climate resulted in a shift in **forest composition**, from ponderosa pine forests to shrublands and woodlands dominated by Gambel oak, piñon pine, and juniper in FireBGCv2-Jemez modeling experiments. Where ponderosa pine stands remained, **forest structure** favored stands dominated by immature, sapling stage trees, with a loss of mature, large trees. Loss of large trees occurred from drought- and heat-induced tree mortality, with some additional losses due to high-severity fire. Such climate change impacts on tree mortality have been well-documented at regional to global scales (Allen et al. 2010, Van Mantgem et al. 2009, Williams et al. 2013, Williams et al. 2010). Changes in forest composition and structure occurred ca AD 2075, corresponding to the hottest and driest period of simulated future climate (see Loehman et al. 2018, Figure 2). By the end of the 100-year simulation periods, **forest productivity** (measured via basal area) was about 10 percent of its initial value. Loss of basal area occurred from a complex of ecological processes - tree mortality, regeneration failure, and compositional and structural shifts to shrublands or early successional forests—caused by climate stress, wildfires, management treatments, and changes in the distribution of bioclimatic space suitable for plant growth.

The modeled LANDIS-II-Kaibab changes in **forest composition** were minimal throughout the simulation period: ponderosa pine was the dominant species regardless of climate or management scenario However, declining regeneration of currently dominant species suggests that the LANDIS-II-Kaibab landscape will also transition to an alternative composition given a longer timeframe (more than the 100-year simulation period). Climate-driven regeneration failure shifted **forest structure** away from younger cohorts and towards already established older cohorts, as climate moved away from the regeneration niches of overstory species. The impact of climate driven regeneration failure was clearly illustrated by declines in **forest productivity** (measured via biomass) in the LANDIS-II-Kaibab landscape. Tree biomass decreased drastically under the Hot-Arid climate scenario and by the end of the century average biomass in managed forests was well below historical estimates of pre-fire suppression biomass for ponderosa pine and dry mixed conifer on the Kaibab Plateau.

Can modeled management strategies maintain historical forest composition, structure, and productivity?

Both FireBGCv2-Jemez and LANDIS-II-Kaibab model simulations found that management had little effect on ecosystem responses to climate change. The current management strategy (BAU scenario, Table 1) was consistently ineffective in preventing changes under future climate. For the FireBGCv2-Jemez, current rates of thinning and prescribed burning treatments had little influence on area burned or high-severity area burned. In the LANDIS-II-Kaibab simulations the higher rates of thinning and burning (3xBAU and 6xBAU; Table 1), reduced wildfire impacts. However, reductions in regeneration and forest productivity reorganized forests regardless of fire impacts. The BAU scenarios were similarly ineffective in preventing biomass declines, shifts in age structure, and compositional changes under future climate. Targeted, intensive treatments may be effective in delaying change for high value landscapes at fine scales. However, the central role of climate in driving forest changes through either mortality or regeneration failure suggests that the benefits of current treatments will likely be temporary.

Our modeling indicates that novel management approaches will be required to facilitate the adaptation of forest to changing climate and fire regimes (Svenning and Sandel 2013, Schoennagel et al. 2017). These novel management approaches may require new objectives that focus on transitioning communities away from historical conditions and towards new composition and structure that is better adapted to warmer temperatures and more frequent fire (Stephenson 2014, Seastedt et al. 2008).

Phase 3: Vulnerability Assessment

Vulnerability assessments (VAs) are used widely by resource managers to identify relative strengths and weaknesses among a suite of resources and to prioritize management actions. Designed to communicate and compare complex interactions and uncertainties, VAs are useful for comparing outcomes under varying environmental conditions or management practices. Before this project, VAs had not been used to evaluate the interactive effects of climate and fire regime changes on landscape components (though Thorne et al. 2018 do include wildfire as a stress factor in their assessment of forest vulnerability to climate change). Given the benefits of using VAs for management decision-making under uncertain futures, we developed the SW FireCLIME Vulnerability Assessment (VA) tool. The SW FireCLIME VA provides a flexible and rapid method for managers who wish to assess climate-related vulnerability in dynamic ecosystems.

The SW FireCLIME VA tool (Friggens et al. 2019) quantifies ecosystem vulnerability based on current and future climate-fire-vegetation relationships as they relate to desired future ecological conditions, to provide inference into which management strategies may be most effective for reducing risk under a changing climate. By identifying which fire regime and ecosystem components are most likely to be affected by climate, and evaluating whether specific management activities may mitigate impacts, the SW FireCLIME VA can provide information critical for planning under changing fire regimes and fuel conditions. Users can calculate the relative vulnerability of different ecosystems to similar fire-climate scenarios, compare multiple climate and management scenarios, and identify the critical drivers of climate-fire and fire-ecosystem responses. The SW FireCLIME VA tool also quantifies uncertainties that may arise due to unknown or ambiguous future conditions or a lack of scientific information on key characteristics. For detailed information on the tool and how to use it please see Friggens et al. (2019).

Materials and Methods

To develop a vulnerability assessment that could address complexities in climate-fire-ecosystem interactions, we engaged in a multistep process that included scientist-manager discussions, conference calls, webinars, and case study applications. First, the conceptual diagram (Fig. 2) that guided the Science Synthesis workshop planning was used to lay down the fundamental pathways that must be included in a new tool. Outcomes of the workshop discussion led to further refinements of key indicators of fire climate interactions and potential outcomes. Following this, we developed several tentative assessment systems that considered various ways to quantify vulnerability, definitions of vulnerability and combinations of potential predictors. The core SW FireCLIME team held several phone calls and in-person meetings including some test runs of early systems. The final SW FireCLIME Vulnerability Assessment considers eight ecosystem characteristics that correspond to vegetation and fuel conditions and responses. In addition, includes 13 measures related to the intrinsic sensitivity of ecosystems and a module that allows users to compare up to three management scenarios (Fig. 8). Once the framework was agreed upon, we applied this system to two case study ecosystems in the Southwest; ponderosa pine in the Jemez Mountains of northern New Mexico and within the Lincoln National Forest of southeastern New Mexico.

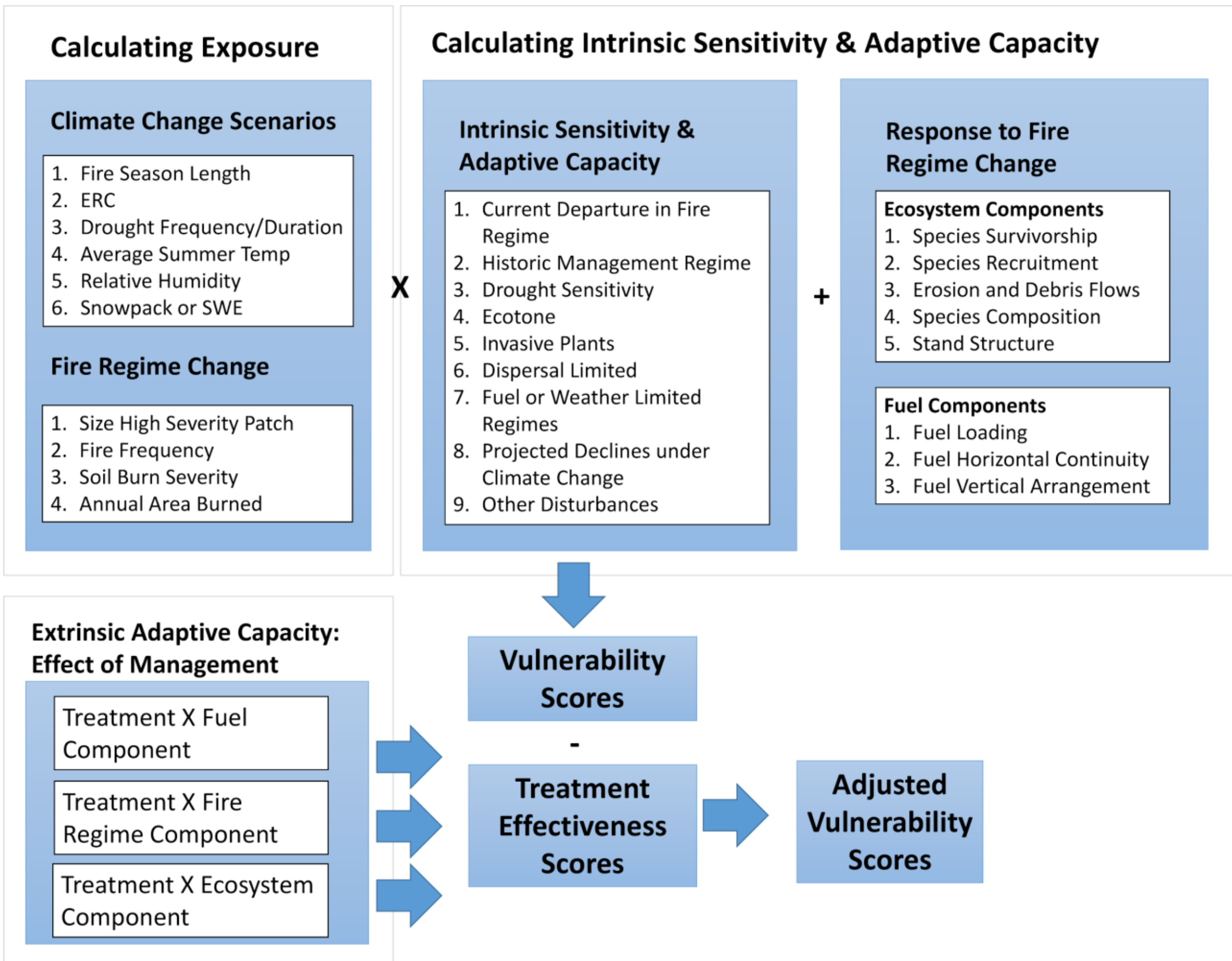

Figure 8. Diagram showing components of the SW FireCLIME VA (from Friggens et al. 2019, Figure 4).

For the Jemez case study, we used recent environmental impact statement documents from the Santa Fe National Forest, NVivo generated summaries, and other primary literature to determine the appropriate responses for the SW FireCLIME tool. From this exercise we were able to determine further refinements to the tool. The new version was applied to similar forest types in the Lincoln National Forest (LNF) in collaboration with LNF forest managers. We applied the SW FireCLIME VA to two project areas identified by the LNF managers: Perk Grindstone and 16 Springs. Both project areas were undergoing fire management treatments. A primary goal for the LNF was to determine whether the ponderosa pine ecosystems of these project areas were vulnerable to climate related changes in fire regimes and identify potential management strategies previously and currently applied to the landscape that may be most effective in reducing the vulnerability of the project landscape. A secondary goal of this effort was to allow the SW FireCLIME team an opportunity to apply the SW FireCLIME VA tool to a real landscape under the direct advisement of fire managers and experts. We conducted three online meetings: the first an introductory webinar, the second and third were facilitated discussions where managers completed the SW FireCLIME VA as a group for each project area. The LNF case studies and analyses are ongoing. For each project area, managers considered three treatments that were previously implemented across different areas of the project, and considered three alternative weighting scenarios that allows LNF managers to compare specific ecological or management priorities and identify differences in the underlying drivers of vulnerability in their ecosystem.

Results and Discussion

Within the SW FireCLIME VA, vulnerability specifically refers to the potential for an ecosystem or its components to move away from desired future conditions; in essence susceptibility of the system to further departure as a result of changing conditions. Further, ecosystem response to disturbance is driven by both internal and external factors. The final SW FireCLIME VA is divided into four primary sections: 1) A *Prework Section* to determine climate change scenarios, desired time period of assessment and Desired Future Conditions (DFC); 2) an *Exposure* section that asks users to identify expected, climate-driven changes in fire regime components for the study system; 3) an *Intrinsic Sensitivity* section that considers ecosystem characteristics that might increase susceptibility to changing conditions; 4) *Response score* sections that are used to measure whether changes will have negative, neutral or positive impacts on the ecosystem. For each of these sections, users indicate their level of confidence with the available literature and knowledge of a given phenomenon. These “confidence scores” represent uncertainty.

A key result of discussions with scientists and managers was that the SW FireCLIME VA must be flexible to a wide range of potential scenarios and conditions. As a result, we design the core measurement of vulnerability around user defined DFC. The primary purpose of the *Prework* section is recording a detailed scenario of DFC so that later sections can consider whether changes in climate and fire and the response to those changes will lead towards or away from DFC; the former representing increasing benefit and the latter increasing vulnerability.

The *Exposure* section records how and to what degree climate and fire regimes will change within an area, and whether a particular change leads to a departure from DFC. This tool does not assume that all fire-climate interactions will result in departure from DFC and, as a result, exposure scores could reflect a number of outcomes. For the purpose of calculating vulnerability, only those scenarios that result in a condition likely to negatively impact ecosystems are carried forward in the tool calculation. The *Intrinsic sensitivity* section considers whether the current status of an ecosystem contributes to the likelihood of a negative outcome (further departure from DFC) when exposed to changes in climate or fire regime. We identified 13 potential indicators of sensitivity. Systems that have more of these sensitivities have a higher intrinsic sensitivity and, ultimately, vulnerability score. The *Response* section considers whether individual ecosystem components will move away or toward DFC as a result of changes to fire regimes. Vulnerability increases when components are expected to move away from DFC in response to changes in fire regime, and decreases when components are expected to move towards DFC. A primary goal for SW FireCLIME VA was to provide a way to estimate how well management actions (treatments) are able to reduce vulnerability. The final section*, Extrinsic adaptive capacity,* provides a way for managers to explore the effectiveness of different management actions. To estimate extrinsic adaptive capacity, the SW FireCLIME VA calculates management impacts for fire regime, ecosystem, and fuel components in the context of DFC. If management actions bring a component closer to DFC, extrinsic adaptive capacity increases and vulnerability decreases. If management actions have no effect, then vulnerability does not change.

Output from the tool includes scores for overall vulnerability of an ecosystem (risk of departure from DFC) and scored values of impact relating to fire regime change and ecosystem response (Fig. 8). Several measures specific to individual component impacts are also produced, which can be used to identify components with the greatest likelihood to be negatively affected by expected changes in climate-fire processes (Fig. 9). Additionally, users are asked to rank their confidence for each response based on the amount of information available to answer the question and the robustness of that information. These confidence scores are then presented in charts so that users can quickly assess the degree of uncertainty associated with the assessment.

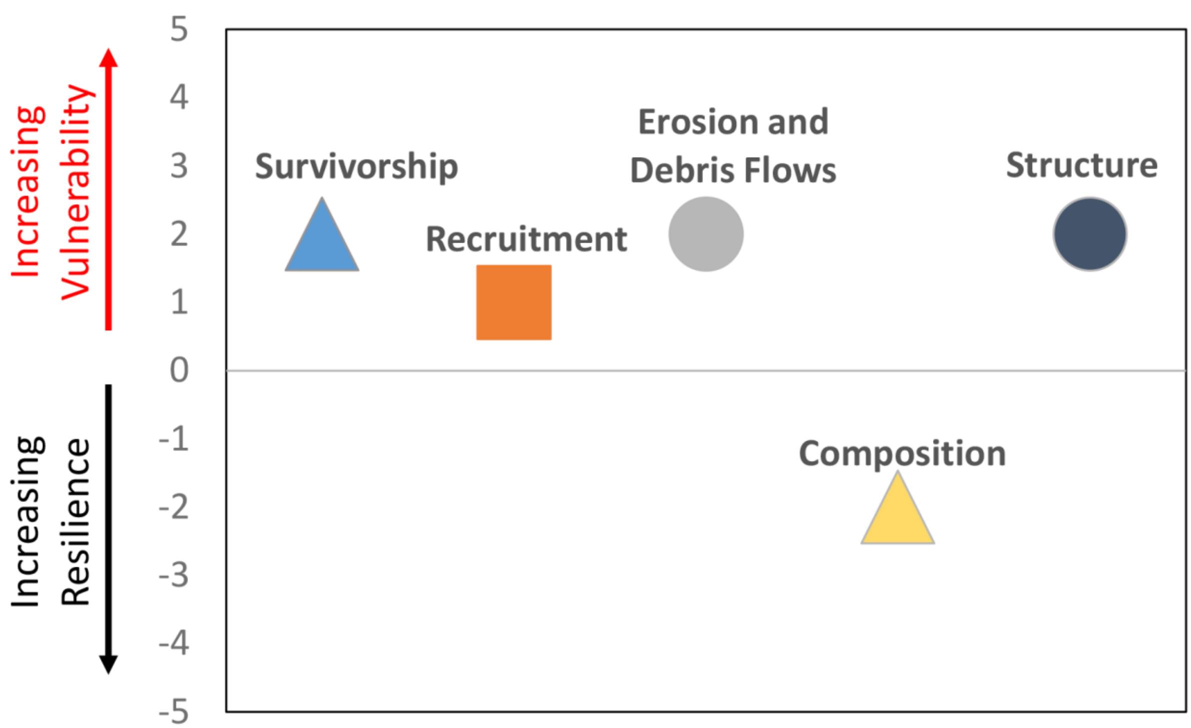

Figure 9. Example output from SW FireCLIME VA tool (from Friggens et al. 2019, Figure 3).

The SW FireCLIME VA is one of the few process driven VAs, meaning it is not looking at the vulnerability of a species, but of the ecological process of fire. It is also the only VA to directly look at climate effects on fire regimes and the resultant ecosystem effects. This unique VA allows managers to “game” their landscapes with future climates and treatments; allowing managers to better understand the vulnerability of their ecosystems to changes in climate and fire regimes. Managers can use the tool to think about how different treatments will affect that vulnerability. For example, managers can compare the vulnerability of different vegetation types (Fig. 10a), different climate scenarios (Fig. 10b), different treatments for one climate scenario (Fig. 10c) or different treatments for different climate scenarios (Fig. 10d). For any of the comparisons made in the SW FireCLIME VA, managers can assess overall vulnerability of each ecosystem component (Fig. 9).

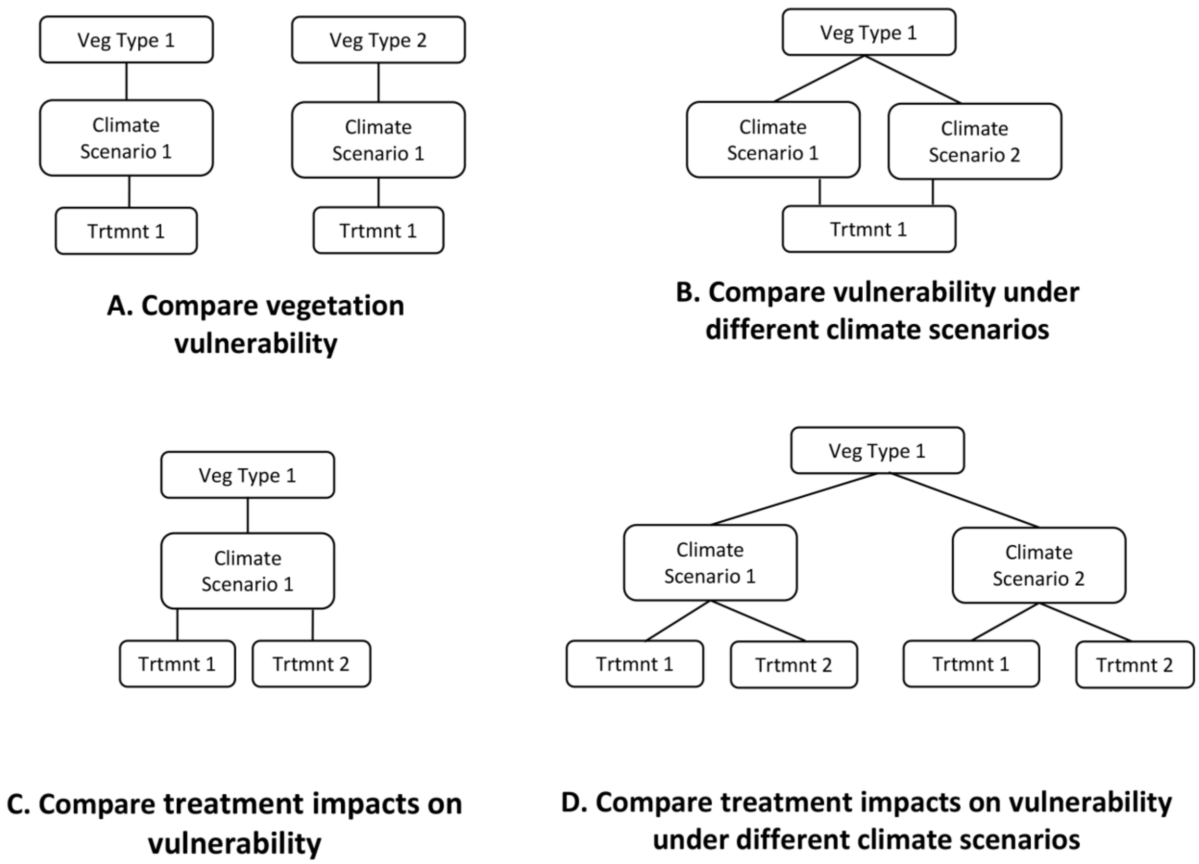

Figure 10. Examples of comparisons that can be made using the SW FireCLIME VA (from Friggens et al. 2019, Figure 2).

Phase 4: Climate Adaptation Tools

This phase of the project focused on how to best integrate tools and information created during SW FireCLIME into a format that is friendly and easily accessible to managers as well as identifying a process to help fire managers move forward with climate adaptation despite uncertainties. Two main products came out of this phase: 1) create a co-designed *Fire-Climate Menu of Adaptation Strategies and Approaches*; 2) test that menu with managers and practitioners to ensure its clarity, usability, and importance. The test was done through a workshop that included the SW FireCLIME science synthesis, modeling, and the Fire-Climate

Menu applied to a specific landscape and project-level goals. The Kaibab Fire & Climate Adaptation Workshop was co-designed and planned by SW FireCLIME, the Northern Institute of Applied Climate Science (NIACS) and the Kaibab National Forest to pilot the new menu of adaptation strategies. Stakeholders (both managers and scientists across agencies, academia, and NGOs) were invited to participate in this three-day workshop exploring climate change impacts and adaptation strategies for fire management on the Kaibab Plateau and provide feedback on our draft menu. This workshop took place in Flagstaff, AZ on February 11th through 13th, 2020.

The overarching goals of the workshop were to:

- Review regional and local effects of climate change on fire in forest ecosystems;
- Explore resources and tools that can be used to integrate climate change into management;
- Understand adaptation concepts and principles in the context of sustainable forest and fire management;
- Identify challenges and opportunities for fire managers; and
- **Develop actionable steps to adapt forests to changing fire regimes.**

Materials and Methods

The *Fire-Climate Menu of Adaptation Strategies & Approaches* builds upon all three of the previous phases (science synthesis, modeling and VA tool). The SW FireCLIME team worked together to generate a list of fire-related adaptation priorities based on individual expertise and the collective outcomes of our research into climate and fire in the Southwest. We also identified fire-focused strategies previously articulated in climate adaptation frameworks that have emerged from the western United States, including the U.S. Forest Service report on Climate Change Vulnerability and Adaptation in the Intermountain Region (Halofsky et al. 2016; Halofsky et al. 2018), and the Climate Change Adaptation Library for the Western United States (http://adaptationpartners.org/library.php).

As a template and inspiration, we used the original Menu of Adaptation Strategies and Approaches for forested ecosystems published alongside the CCRF process in Swanston et al. (2016). Looking at the priorities identified by our group, as well as what we pulled from other adaptation sources, we grouped strategies based on the thematic structure of the original menu (Swanston et al. 2016). With additional review and input from the climate science and adaptation experts behind the CCRF, we emerged with a draft menu and debuted it at the Association for Fire Ecology conference in November, 2019.

An updated version of the fire menu was first piloted in the CCRF Adaptation Workbook process (Fig. 11) at the February, 2020 workshop (31 participants). The workshop focused on the Kaibab National Forest's Kaibab Plateau Ecosystem Restoration Project (KPERP). In the process, manager participants were able to provide us with valuable feedback about the utility of the fire menu in facilitating this step. In addition to group discussion, we used a brief survey to solicit recommended revisions to the menu. We have incorporated those suggestions, as well as another round of comments from our expert group of scientists and managers. At this stage, we feel that the fire menu represents a thorough picture of the current state of knowledge on adaptation to climate-induced fire regime change, drawing from decades of management and research experience.

Figure 11. Participants at the February, 2020 Kaibab Fire and Climate Adaptation Workshop

KPERP Workshop Process

The workshop followed the CCRF Adaptation Workbook Process (forestadaptation.org/adapt/adaptation-workbook), which was developed to enable natural resource professionals to consider the potential effects of climate change on the lands they manage and to then design actions that can help reduce risk and increase their ability to cope with changing conditions (Swanston et al. 2016; Janowiak et al. 2014). The Adaptation Workbook follows an adaptive management framework and walks participants through five key steps:

1. Defining goals and objectives;
2. Assessing climate impacts and vulnerabilities;
3. Evaluating objectives considering challenges and opportunities of local climate impacts;
4. Identifying adaptation approaches and tactics for implementation; and
5. Monitoring effectiveness of implemented actions.

The fourth step of this workshop process utilizes "menus" of adaptation strategies and approaches, allowing managers to identify their adaptation intentions and develop and implement their own specific adaptation actions by choosing approaches that are most suitable to a particular management goal and on-the-ground conditions. It is up to the individual group using the menu to select the appropriate actions for a specific project and their locally-specific goals. This step is where the Southwest FireCLIME "Fire Menu of Adaptation Strategies & Approaches" was piloted with the implementation units selected from the KPERP project.

In addition, a pre-workshop webinar was held to share outcomes from the synthesis, modeling and vulnerability phases of SW FireCLIME that were pertinent to the workshop.

Results and Discussion

The current version of the Fire-Climate Adaptation Strategies and Approaches is available on the SW FireCLIME website (https://swfireclime.org/). By design, this menu is a flexible, living document. We encourage modification, innovation, and creativity. Catalyzing new ideas is just as much of a goal as sharing existing ones. The ten strategies and 29 supporting approaches that we have identified are outlined in Table 3. However, this work is currently being written up for publication and this list of Strategies and Approaches may have changes. The tactics nested under each approach are not shown here, but are where the detailed implementation plans become more clear. The tactics are where we would expect the most changes as this menu is used in different ecosystems around the country. Please refer to the website for the most updated version over time.

Table 3. Strategies and approaches for climate and fire adaptation

Strategy	Approach
Strategy 1: Sustain fire as a fundamental ecological process	Approach 1.1: Restore or maintain fire in fire-adapted ecosystems
	Approach 1.2: Develop fire use strategies in altered or novel ecosystems where fire can play a beneficial role
Strategy 2: Reduce the effects of biotic and abiotic stressors on fire regimes	Approach 2.1: Prevent the establishment and spread of nonnative invasive species that alter fuel regimes and remove existing populations
	Approach 2.2: Maintain or improve the ability of forests to resist pests and pathogens that may alter fuel regimes
	Approach 2.3: Limit, selectively apply, and monitor land uses that increase fire risk or threaten fire resilience
Strategy 3: Reduce the risk of unacceptable fire	Approach 3.1: Protect fire-sensitive ecosystems from fire
	Approach 3.2: Alter forest structure and composition to reduce the risk of unacceptably severe fire
	Approach 3.3: Establish fuel breaks to stop the spread of unacceptable fire
Strategy 4: Limit the effects of unacceptable fire and promote post-fire recovery	Approach 4.1: Promote habitat connectivity and increase ecosystem redundancy
	Approach 4.2: Maintain or create fire refugia
	Approach 4.3: Stabilize and enhance the physical fire footprint
	Approach 4.4: Promote recovery of native vegetation and habitat
Strategy 5: Maintain and enhance structural, community, and species diversity	Approach 5.1: Maintain or increase structural diversity from stand to landscape scales
	Approach 5.2: Promote diversity within and among communities
	Approach 5.3: Maintain or restore diversity of native tree and understory plant species
Strategy 6: Identify, promote, and conserve fire resilient species and genotypes	Approach 6.1: Promote native species and genotypes that are better adapted to future climate and fire regimes, disfavor species that are distinctly maladapted
	Approach 6.2: Use plant materials from regional areas that have current climate and fire regimes similar to your anticipated future conditions
	Approach 6.3: Increase seed banking to preserve fire resilient species and genotypes
Strategy 7: Facilitate ecosystem adaptation to expected future climate and fire regimes	Approach 7.1: Facilitate the movement of species that are expected to be adapted to future conditions and fire regimes
	Approach 7.2: Consider using fire as a tool to align existing vegetation communities with changing climate and fire regimes
Strategy 8: Use fire events as opportunities for ecosystem realignment	Approach 8.1: Revegetate burned areas using fire-tolerant and drought-adapted species and genotypes
	Approach 8.2: Allow for areas of natural regeneration to test for future-adapted species

	Approach 8.3: Realign ecosystems that have undergone post-fire vegetation type conversion to meet expected future conditions
Strategy 9: Promote organizational and operational flexibility	Approach 9.1: Develop adaptive staffing and budgeting strategies
	Approach 9.2: Explicitly consider future and changing climate and fire regimes during the planning process and adaptive management cycle
Strategy 10: Promote fire-adapted human communities	Approach 10.1: Increase fuel reduction treatments in the wildland-urban interface (WUI)
	Approach 10.2: Actively promote broad social awareness and increase education about anticipated effects of climate change on fire regimes

KPERP Workshop Synthesis and Outcomes

Each breakout group worked their way through the NIACS Adaptation Workbook process over the three-day workshop, starting with defining their specific management goals, objectives, and desired future conditions. Some of the crosscutting management goals included:

- Restoring natural fire regimes
- Maintaining resilient forests by reducing the risk of high intensity wildfire
- Protecting the wildland urban interface
- Promoting heterogeneity

Groups discussed the climate change impacts that were of most concern for their project areas, which included:

- Warmer annual and seasonal temperatures
- Increase in drought and heat-induced tree mortality
- Increase in pest and pathogen induced tree mortality
- Increase in vapor pressure deficit and decrease in relative humidity
- Increase in area burned at high severity
- Earlier snowmelts
- Increase in fire season length

These climate change impacts pose both challenges and opportunities for management on the Kaibab Plateau, including:

Challenges

- Variable burn windows could create conflicts with hunting season and goshawk nesting season, and the potential to move out of prescription on hotter, drier days
- Capacity issues may occur trying to match the workforce with treatment needs
- Climate change impacts might result in a loss of the mesic mixed conifer ecosystem before management can be implemented

Opportunities

- Variable burn windows might also provide the opportunity to accomplish more work on-the-ground, and there may be increased cool season burn windows

- Changing conditions will allow managers to try untraditional burning technique

Workshop participants used these challenges and opportunities presented by climate change impacts to inform the adaptation strategies and approaches chosen for each implementation unit. Some of the strategies and approaches selected by multiple breakout groups included:

- STRATEGY 1: SUSTAIN FIRE AS AN ECOLOGICAL PROCESS
  - APPROACH 1.1: Restore or maintain fire in fire-adapted ecosystems
- STRATEGY 3: REDUCE THE RISK OF UNACCEPTABLY SEVERE FIRE
  - APPROACH 3.1: Alter forest structure and/or composition to reduce the risk of unacceptably severe wildfire
- STRATEGY 5: MAINTAIN AND ENHANCE STRUCTURAL, SPECIES, AND COMMUNITY DIVERSITY
  - APPROACH 5.2: Maintain or increase structural diversity at the landscape scale
- STRATEGY 7: FACILITATE ECOSYSTEM ADAPTATION TO EXPECTED FUTURE CLIMATE AND FIRE REGIMES
  - APPROACH 7.1: Promote native species that are expected to be resilient to future climate and fire regimes
  - APPROACH 7.4: Consider using fire as a tool to align vegetation communities with changing climate regimes
- STRATEGY 9: PROMOTE ORGANIZATIONAL AND OPERATIONAL FLEXIBILITY
  - APPROACH 9.1: Develop adaptive staffing and budgeting strategies

Finally, to connect the dots of the Adaptation Workbook Process and show intentionality of actions, each group suggested a monitoring variable and criteria to measure success of on-the-ground actions.

Lessons Learned

By the end of the three-day workshop, participants had suggestions for how to improve the Fire-Climate Adaptation Menu, next steps individuals would take following the workshop, and next steps for the larger group to pursue to advance climate and fire adaptation on the Kaibab Plateau. A few of these lessons learned included:

- Reframing historic or natural range of variability to managing for a "future range of variability;"
- Collecting more data on forest transitions that have already occurred across the Kaibab Plateau to better learn from those shifts and inform future management;
- Coordinating monitoring efforts across the Kaibab Plateau to determine the management questions that most need addressing moving forward; and
- Creating a Kaibab Climate Workgroup that can keep these conversations, science, and management efforts around fire and climate adaptation moving forward into the future, including communicating resistance, resilience, and transition with additional audiences across the Kaibab Plateau.

Valuable comments and edits were gathered and used to update the Fire-Climate Adaptation Menu and we are currently working on publishing the menu to share it with a wider audience. We believe the menu will be useful nationally and can continue to be updated as it is used, and more is learned.

All materials and presentations from the workshop can be found on our SW FireCLIME website (https://swfireclime.org/kaibab-fire-climate-adaptation-workshop/) and the CCRF website at https://forestadaptation.org/learn/kaibab-fire-and-climate-adaptation-workshop.

Key Findings

Phase 1: Science Synthesis

1. The key finding from the development of the annotated bibliography is the understanding that linkages between climate, fire regimes and ecosystems are essential to both the science and management of fire on heterogeneous landscapes. The complexity of these linkages is important to the scientific community for understanding fire as a biophysical process, but it can also be a barrier to formulating, planning, and implementing climate adaptation strategies.

2. At the same time, our research underscores that fire regimes vary systematically across gradients of elevation and climate, reflecting the distribution of plant communities as well as the physical controls on fuel production and flammability. This landscape variation can be useful in predicting future shifts of fire regimes under altered climate.

Phase 2: Modeling interactions of climate, fire, and ecosystems

1. Persistent shifts in forest composition, structure, and biomass of dry conifer forests are likely, (as compared with present-day southwestern landscapes) caused by climate changes and shifting fire patterns.

2. We found resilience traits in dry mixed conifer forests in both model landscapes, and indications that ecotonal zones—for example, the piñon-juniper/ponderosa pine ecotone in the Jemez Mountains—can facilitate relatively rapid upslope movement of drought-adapted species into areas that have become too arid to support more mesic forests.

3. Models produced dissimilar outcomes related to management and climate impacts on fire regimes, the result of inherent differences in model mechanics. However, both models captured cumulative, reciprocal interactions of climate, fires, and vegetation that highlight the complexity of fire-prone ecological systems in which key driving processes (e.g., climate) have both direct and indirect and short- and long-term influence on landscape patterns and processes.

4. Our results are compatible with recent papers that have identified the need for new strategies to promote the resilience of fire-prone forested ecosystems. Current and intensified management treatments simulated for FireBGCv2-Jemez and LANDIS-II-Kaibab did not prevent fundamental reorganization of the study landscapes under changing climates, suggesting that historical or present-day forest and fire regime characteristics may not be achievable management targets in the future.

Phase 3: Vulnerability Analysis

The development of the SW FireCLIME Vulnerability Assessment Tool facilitates the first step toward implementing an adaptive management framework. Key findings of this process include:

1. Through an iterative process involving repeated discussions, we identify predictors of ecosystem vulnerability based on the best available science.

2. Management needs vary across landscapes and agencies and to ensure maximum application, vulnerability assessments need to allow for a range of potential targets. For our application, we determined Desired Future Condition was an appropriate target to use to determine potential negative impacts.

3. The use of the SW FireCLIME VA can lead to information on the specific ways in which an ecosystem may be negatively impacted by fire-climate interactions that directly inform the selection of adaptation strategies.

4. This vulnerability assessment, like many others, is most useful when used in an iterative way to compare multiple climate or management scenarios.

5. The structure and features of vulnerability assessment tools can shift over the course of the development process as the realities of manager needs and scientific knowledge become better understood. For the SW FireCLIME VA, predictors of vulnerability were restricted in part by availability of scientific information. The final VA structure, composed of both intrinsic and response-based measures of sensitivity and adaptive capacity, was a necessary modification to ensure the VA considered predictors in context of real management actions.

Phase 4: Climate Adaptation Tools

Identifying an excellent climate adaptation framework, creating a menu of fire-climate adaptation strategies, and applying both to a real-world scenario resulted in four key insights.

1. The Climate Change Response Framework (CCRF) developed at the Northern Institute of Applied Climate Science (NIACS) proved to be a highly adaptable framework that was extraordinarily well-matched to both existing SW FireCLIME products, and our need to translate outcomes into actionable information for the management community.

2. Generating a list, or 'menu' of fire-specific climate adaptation strategies, approaches, and tactics enabled us to systematically review the results and outcomes of the first three phases of SW FireCLIME through the lens of managers implementing treatments on the ground. This resulted in a concise set of options spanning the adaptation spectrum from resistance to resilience to transition, which was well-received and positively reviewed by workshop participants.

3. The menu and adaptation workbook process provided an effective framework for managers to think about where landscapes might be more static to where they may see transitions to new vegetation types and ecosystems. The diversity of adaptation

strategies and approaches chosen for each implementation unit during the workshop demonstrated the utility for land management decision making.

4. Partnering with NIACS and leveraging existing tools and expertise enabled us to maximize the impact of our science without duplicating efforts. This partnership has been mutually beneficial and has already resulted in ideas for future collaboration.

Implications for Management and Policy

Phase 1: Science Synthesis

Managers and policy makers need to be able to access the pertinent science quickly and easily. However, this is a daunting task given the extent of the climate change and fire literature for the Southwest, much less the country or globe. SW FireCLIME has made that task less imposing. **The annotated bibliography (www.frames.gov/swfireclime/bibliography) allows planners to search and directly access the literature that is relevant to the linkage and question they need information on. Managers working to implement planning can search to find literature that is pertinent to their projects and goals on the ground.** The bibliography is designed so it is easier to add new literature as summaries become available.

The soon-to-be released analysis of how fire regimes respond to climate differently across elevation and biophysical gradients will assist managers trying to predict future patterns and variability in fire regimes as climate changes.

Phase 2: Modeling interactions of climate, fire, and ecosystems

Our results confirm **the need for new strategies to promote the resilience of fire-prone forested ecosystems**. Current business-as-usual, or even a six-fold increase in treatments in our models did not prevent vegetation type changes. This means historical or present-day forest and fire regime characteristics may not be achievable management targets. The design of new management approaches presents two important challenges. First, it requires consensus on achievable objectives under future climate conditions, not based on historic reference conditions. Potential objectives could include the maintenance of functional types or ecosystem services, biomass conservation, carbon sequestration, the maintenance of key habitats, or the conservation of species diversity. Second, managers would need to begin implementing and experimenting with untested approaches that could produce unintended consequences.

Modeling studies will be an important component of climate adaptation, helping to inform the selection of promising treatments and anticipate risks. However, ultimately, these approaches will require testing in actual landscapes. This approach poses a difficult but critical path forward, requiring a dynamic, experimental land management framework that anticipates change, acknowledges that current systems will transform away from historical references, and allows dynamic ecological processes to occur. Monitoring will need to be a critical piece of this path forward. Strategies, approaches, and tactics that can be used for planning and implemented now were developed and tested in our Climate Adaptation Tools phase (Phase 4).

Phase 3: Vulnerability Analysis.

Vulnerability Assessments are a critical first step within an adaptation planning cycle and the SW FireCLIME VA is ready for managers to use across the Southwest (swfireclime.org/vulnerability-assessment/). **The SW FireCLIME VA allows managers to not only identify most vulnerable vegetation types but what makes them vulnerable.** The SW FireCLIME VA tool scores ecosystems based on current and future expected climate-fire-vegetation relationships as they relate to user inputs about desired future conditions to provide inference into which management strategies may be most effective for reducing risk under changing climate conditions. By identifying which fire regime and ecosystem components are most likely to be affected by climate, and which treatments are able to mitigate impacts, the SW FireCLIME VA can provide information critical for planning under changing fire regimes and fuel conditions. Results of vulnerability assessments directly inform the selection of Adaptation Strategies identified in Phase 4 of this project.

Phase 4: Climate Adaptation Tools.

The Climate-*Fire Menu of Adaptation Strategies & Approaches* (swfireclime.org/fire-climate-adaptation-tools/) allows managers to look at specific projects and to select from a range of strategies, approaches, and tactics to incorporate climate change into their management actions. These actions can be as common as using prescribed fire to maintain frequent fire to planting seedlings in post-fire landscapes that are more adapted to drought conditions. It often seems the barriers to implementing climate adaptation in project-level work is that the idea of incorporating climate change brings a tremendous amount of uncertainty. The Climate-Fire menu helps show strategies that are useful for a range of future climate effects, from keeping the status-quo to vegetation type conversion.

Future Work

The SW FireCLIME project highlights the effectiveness of science-management co-production of knowledge and the need for continued support for this work. Similarly, the need for decision support tools developed with managers is great, and this project has moved that forward but more needs to be done. Models need continued refinement, and even more importantly, testing in new landscapes to expand this work. Continuing to include managers in the modeling process will build confidence in results and facilitate model-guided implementation. Similarly, this was a first attempt at a process driven VA for fire-climate interactions. This VA will need to be refined and updated. Equally important is support for researchers to work with managers to use VAs at the project level. The SW FireCLIME project demonstrated investment by researchers in assisting managers use of VAs pays dividends for both science and implementation.

SW FireCLIME has started the work of helping managers to implement climate adaptation strategies in the Southwest, but this is the land management challenge of our generation and more work is urgently needed. Given agency resource (time and money) limitations, how can we better facilitate agency use of tools and information produced in this effort? What are the next steps identified by the management community? The conversation is not complete and additional workshops and scientist/manager partnerships are needed to continue to move this work forward.

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Appendix A: Contact Information for Key Project Personnel

Andrea Thode - PI
School of Forestry
Northern Arizona University
P.O. Box 15018
Flagstaff, AZ 86011
andi.thode@nau.edu

Rachel Loehman
US Geological Survey, Alaska Science Center
333 Broadway SE Suite 115
Albuquerque, NM 87102
rloehman@usgs.gov

William Flatley
Department of Geography
University of Central Arkansas
201 Donaghey Ave
Conway AR, 72035
wflatley@uca.edu

Megan Friggens
USFS Rocky Mountain Research Station
Albuquerque Sciences Lab
333 Broadway SE
Albuquerque, NM 87102
megan.friggens@usda.gov

Alexander Evans
Forest Stewards Guild
2019 Galisteo St; Ste N7
Santa Fe, NM 87505
zander@forestguild.org

Larissa Yocom
Department of Wildland Resources
Utah State University
5230 Old Main Hill
Logan, UT 84321
larissa.yocom@usu.edu

Peter Fulé
School of Forestry
Northern Arizona University
P.O. Box 15018

Flagstaff, AZ 86011
pete.fule@nau.edu

Windy Bunn
National Park Service
Interior Regions 6, 7, and 8
12795 West Alameda Parkway
Lakewood, CO 80228
windy_bunn@nps.gov

Shaula Hedwall
U.S. Fish and Wildlife Service
2500 South Pine Knoll Drive
Flagstaff, AZ 86001
shaula_hedwall@fws.gov

Donald Falk
School of Natural Resources and the Environment
Environment and Natural Resources Building 2
University of Arizona
Tucson, AZ 85721 USA
dafalk@arizona.edu

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Articles in peer-reviewed journals:

Loehman, R., Flatley, W., Holsinger, L., Thode, A. 2018. Can Land Management Buffer Impacts of Climate Changes and Altered Fire Regimes on Ecosystems of the Southwestern United States? *Forests*. 9(4): 192 doi:10.3390/f9040192

- PDF available: https://swfireclime.org/wp-content/uploads/2020/04/Loehman_Flatley-et-al-2018_Impacts-of-Climate-Changes-and-Altered-Fire-Regimes-on-SW-Ecosystems.pdf

Sample, M., Thode, A., Peterson, C., Loehman, R., Flatley, W., Evans, A., Swanston, C. 2020. Adaptation Strategies and Approaches for Changing Climate and Fire Regimes in the Southwest United States. *Manuscript in preparation.*

Yocom, L., Falk, D., Thode, A. 2020. Contrasting gradients of productivity and flammability drive forests and fire regimes in southwestern North America. *Manuscript in preparation.*

Technical reports:

Friggens, M., Loehman, R., Thode, A., Flatley, W., Evans, A., Bunn, W., Wilcox, C., Mueller, S., Yocom, L., Falk, D. 2019. User guide to the FireCLIME Vulnerability Assessment (VA) tool: A rapid and flexible system for assessing ecosystem vulnerability to climate-fire interactions. Gen. Tech. Rep. RMRS-GTR-395. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 42 p.

- PDF available: https://swfireclime.org/wp-content/uploads/2020/04/FireCLIME_VA_GTR.pdf

Flatley, W., Mueller, S., Evans, A., Loehman, R., Sample, M., Yocom, L., Friggens, M., Falk, D., Thode, A., 2020. Southwest FireCLIME Annotated Bibliography: A synthesis of research findings describing climate, fire, and ecosystem interactions. General Technical *Report in preparation.*

Textbooks or book chapters:

N/A

Graduate thesis:

N/A

Conference or symposium proceedings scientifically recognized and referenced:

N/A

Conference presentations:

Special Session: *Southwest FireCLIME: A Research Partnership Evaluating Fire-Climate Change Dynamics and Management Implications in the Southwest*. Association for Fire Ecology 8th International Fire Ecology and Management Congress. November 2019, Tucson, AZ.

Abstract: *Southwest FireCLIME is a multi-year research partnership between regional scientists and managers with the goal of evaluating how fire regimes and fuels will shift across Southwest landscapes as climate changes, and assessing the implications of anticipated changes for resource managers. The project began with a comprehensive synthesis of existing scientific understanding of climate, fire regime, and ecosystem interactions. This work was then used to inform multiple modeling techniques across the study region. Across the board, results suggest that changing the scale or intensity of traditional management approaches will be insufficient to prevent the anticipated impacts of climate change on Southwestern ecosystems and natural resources. Presenters from the FireCLIME team will share research results, as well as newly developed tools to support*

management planning and decision-making, including an interactive Vulnerability Assessment tool and a set of Fire & Climate Adaptation Strategies.

- Oral presentation 1: Thode, A. *Landscape Impacts of Fire and Climate Change in the Southwest: A Science-Management Partnership*. https://swfireclime.org/wp-content/uploads/2020/04/Thode_FireCLIME_AFE2019.pdf

- Oral presentation 2: Yocom, L. *Gradients of productivity and flammability drive fire regimes in the Southwest U.S.* https://swfireclime.org/wp-content/uploads/2020/04/Yocom_AFE2019.pdf

- Oral presentation 3: Friggens, M. *The FireCLIME VA: Applying a rapid and flexible system for assessing ecosystem vulnerability to Climate-Fire Interactions to National Forests* https://swfireclime.org/wp-content/uploads/2020/04/Friggens_AFE2019.pdf

- Oral presentation 4: Flatley, W. *Using landscape models to inform climate adaptation strategies in the Southwest* https://swfireclime.org/wp-content/uploads/2020/04/Flatley_AFE2019-1.pdf

- Oral presentation 5: Sample, M. *Adaptation strategies for climate & fire in the Southwest* https://swfireclime.org/wp-content/uploads/2020/04/Martha-AFE-2019-slides.pdf

Loehman, R., Flatley, W., Holsinger, L., Keane, B. *Can fire and fuel management maintain or restore ecological resilience under a changing climate?* Oral presentation as part of the Special Session: Assessing landscape change under changing climates with the spatial process model FireBGCv2. Fire Continuum Conference. May 2018, Missoula, MT.

Loehman, R. & Haire, S. *The fate of fire refugia in future, warmer climates: Modeling spatial patterns and thresholds of disturbance-resistant areas in the Jemez Mountains, New Mexico USA.* Oral presentation (invited) as part of the Special Session: Fire refugia: Identification, formation, function, and management. Fire Continuum Conference. May 2018, Missoula, MT.

Flatley, W., Loehman, R., Holsinger, L., Thode, A., Evans, A., Falk, D., Friggens, M., Bunn, W., Wilcox, C. *Modeling Novel Fire Management Approaches in a Changing Southwest Climate.* Oral presentation at the Annual Meeting of the American Association of Geographers. April 2018, New Orleans, LA. https://swfireclime.org/wp-content/uploads/2020/04/Flatley_AAG_modeling-presentation.pdf

Flatley, W., Loehman, R., Holsinger, L., Thode, A., Evans, A., Falk, D., Friggens, M., Bunn, W., Wilcox, C. *Modeling fire and forests in a warmer world: will management be effective?* Oral presentation at the Association for Fire Ecology 6th International Fire Ecology and

Management Congress. November 2017, Orlando, FL. https://swfireclime.org/wp-content/uploads/2020/04/Flatley_AFEOrlando_modeling_presentation.pdf

Loehman, R., Friggens, M., Thode, A., Flatley, W., Evans, A., Falk, D., Wilcox, C., Bunn, W. *Using Vulnerability Assessments to Link Science and Management.* Oral presentation at the Association for Fire Ecology 6th International Fire Ecology and Management Congress. November 2017, Orlando, FL.

Posters:

N/A

Workshops:

Southwest FireCLIME Science Synthesis Workshop. September 2016. Albuquerque, NM.

This workshop of regional scientists and managers (47 attendees) set out to synthesize current understanding of climate, fire, and vegetation (fuel) dynamics, building from existing literature, ongoing studies, professional experience, and field observations. The gathering helped to solidify the science basis for the remaining project phases and began to address management needs for a comprehensive reference on changing conditions.

Kaibab Climate-Fire Adaptation Workshop. February 2020. Flagstaff, AZ.

https://swfireclime.org/kaibab-fire-climate-adaptation-workshop/

We partnered with the climate adaptation experts at the Northern Institute of Applied Climate Science (NIACS) and managers from the Kaibab National Forest to plan and facilitate a participatory workshop addressing Climate-Fire Adaptation on the Kaibab Plateau. Managers from the North Kaibab ranger district, as well as Grand Canyon National Park and other neighboring jurisdictions, gathered over three days to:

- *Review regional and local effects of climate change on fire in forested ecosystems*
- *Understand adaptation concepts and principles in the context of sustainable forest and fire management*
- *Identify challenges and opportunities for fire managers*
- *Explore resources and tools that can be used to integrate climate change into fire management*
- *Develop actionable steps to adapt forests to climate-induced changed to fire regimes*

Field demonstrations/tour summaries:

N/A

Website development:

Southwest FireCLIME project website: https://swfireclime.org/

We built a project website intended to share the products and results of FireCLIME with the manger partners that we have been working with over the course of the project, as well as the broader fire research and management communities in the Southwest. The website is organized by each phase of the project: science synthesis, modeling, vulnerability assessment, and adaptation tools. It also links to the FireCLIME annotated bibliography site hosted by FRAMES (described in further detail below). Publications, interactive tools, presentation slides, webinar recordings, and event descriptions are all available to view and download from the site.

Southwest FireCLIME Annotated Bibliography (FRAMES): https://www.frames.gov/swfireclime/bibliography

Working with the web developers and data scientists behind the Fire Research and Management Exchange System (FRAMES), we built an interactive and searchable annotated bibliography website that includes publications identified by the FireCLIME team as have relevance to one or more climate, fire regime, and/or ecosystem effects variables. These papers are summarized through the lens of climate-induced fire regime changes and their ecosystem effects, and the specific connections between variables described in the publication are outlined. We hope that this will become a living database that continues to grow as more research related to these topics is conducted and published.

Presentations/webinars/other outreach/science delivery:

- Success Story Video: Southwest FireCLIME (final url is pending)
- Webinar: *Adaptation Strategies for Climate & Fire in the Southwest.* May 2020. Hosted by the Southwest Fire Science Consortium. https://www.frames.gov/catalog/61199
- Invited virtual presentation: *Adaptation Strategies for Climate & Fire in the Southwest*. March 2020. Zoom presentation to the USFS Region 9 Climate Coordinator monthly meeting.
- Webinar: *Regional climate trends and projections: implications for adaptation.* February 2020. Hosted by the Southwest Fire Science Consortium.

- Webinar: *Southwest FireCLIME Vulnerability Assessment.* August 2018. Hosted by the Southwest Fire Science Consortium.
  https://www.youtube.com/watch?v=LEUF0Dk_cic&feature=youtu.be
  https://www.frames.gov/catalog/61168

- Webinar/virtual workshop: *Lincoln National Forest Vulnerability Assessment Workshop*. September 2018.

  An overview of the FireCLIME VA framework and tool presented by PI Megan Friggens, followed by an interactive session on its application to the Lincoln National Forest with USFS managers led by PI Craig Wilcox.

- Targeted outreach to fire managers and researchers: April – December 2017.

  Communication between lead modeling PIs (Will Flatley and Rachel Loehman) and regional fire experts to help guide development of management scenarios for climate and fire modeling work.

- Webinar: *Modeling fire and forests in a warmer world: will management be effective?* August 2017. Hosted by the Southwest Fire Science Consortium.

  https://swfireclime.org/wp-content/uploads/2020/04/FireCLIME-modeling-webinar-slides-0817.pdf

Appendix C: Metadata

Metadata for this project is in draft form and will be submitted to the Rocky Mountain Research Station website (http://www.fs.usda.gov/rds/archive/). The modeling portion of the project is the only portion with data that needs to be archived. GIS datasets used for modeling in both LANDIS-II and FireBGCv2 will be included in the archive. Draft versions of select metadata have been sent to the RMRS for review before completing the archive. Those drafts are uploaded into the JFSP system.